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CONVECTIVE HEAT TRANSFER IN HYPOBARIC ENVIRONMENTS

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ABSTRACT

This study examined the relationships between convective heat transfer and barometric pressure (P_b), specifically, how hypobaric pressure affects the convective heat transfer coefficient (h_c). The U. S. Army Research Institite of Environmental Medicine - High Elevation Simulation Facility was used to simulate five environmental conditions: at elevation of 0 (sea level), 1520 m (5,000 ft), 3050 m (10,000 ft), 4570 m (15,000 ft), and 6100 m (20,000 ft). In the chamber, constant temperature (30°C) and wind speed (0.5 m/s) were maintained. The convective heat transfer coefficient was determined using the naphthalene sublimation technique. Circular naphthalene disks were affixed to six sites on a stationary copper manikin. The amount of naphthalene weight loss through sublimation was translated to h_c using the Chilton-Colburn j-factor analogy between heat and mass transfer. As elevation increases, P_b decreases; h_c should decrease accordingly, pointing to a diminished convective heat transfer mechanism. Hitherto, the relationship between h_c and P_b was thought to be a nonlinear power function. Our results showed that convective transfer indeed decreased at higher elevation, but h_c and P_b exhibit a linear relationship. A linear relationship was also obtained from a theoretical derivation. These results suggest that in a hypobaric environment, the convective transfer process becomes even more diminished, and the potential convective heat loss is smaller than the original nonlinear theory would predict.

Index terms: convective heat transfer coefficient, barometric pressure, heat-mass transfer analogy, Chilton-Colburn j-factor

Heat exchange between the human body and the environment not only depends on the more familiar factors such as temperature, wind speed and humidity, but also is affected by barometric pressure (P_b). The interaction between convective heat transfer coefficient (h_c) and P_b has received little attention, as evident by the limited information available in the literature. While it is known that as elevation increases, P_b decreases, hence h_c also decreases resulting in a reduced convective heat transfer process; the exact manner of this dependency is uncertain. This study looked at, both experimentally and theoretically, the relationship between convective heat transfer and barometric pressure, specifically, how hypobaric P_b affects h_c.

METHOD

Experiment

The U. S. Army Research Institute of Environmental Medicine (USARIEM) High Elevation Simulation Facility (altitude chamber) was used to simulate five environmental conditions: at sea level (760.0 mmHg), at elevation of 1520 m (5,000 ft, 632.4 mmHg), 3050 m (10,000 ft, 522.8 mmHg), 4570 m (15,000 ft, 429.1 mmHg), and 6100 m (20,000 ft, 349.5 mmHg). For all five environments, the chamber ambient temperature (T_a) was maintained at 30°C, relative humidity 20% (dew point ≈5°C). This high temperature was necessary to facilitate the naphthalene sublimation process. At 30°C, most human subjects will, to a greater or lesser extend, perspire. Once perspiration occurs, it invariably contaminates the naphthalene, and renders any naphthalene weight measurement useless. To avoid the problem of perspiration contamination, a life-size (1.68 m^2 surface area)

stationary copper manikin was placed in the altitude chamber to model the surface area dimension and the passive dry heat loss of a human subject. Since we were interested only in the convective heat loss, a manikin also eliminated any evaporative contribution generally involved with human subjects. A circular fan aided in regulating the regional air velocity to between 0.4 and 0.6 m/s, depending on different body segments of the manikin. These levels of air velocity (see Table 1) must be maintained throughout all five hypobaric environments.

Circular naphthalene disks were attached to six sites: upper arm, lower arm, thigh, calf, chest, and back, on the manikin. The Figure 1 schematic shows locations of five of the six naphthalene disks. Placement of the back disk mirrored exactly the chest disk. The naphthalene disks (except chest and back disks) were appropriately curved to conform to the corresponding body segment curvature. Airflow was directed normally at the disk surface. Since the naphthalene disk conformed to the body segment curvature and sat directly over the specific body site, the local h_c over the specific site was measured, rather than an average h_c for the entire body segment. The regional air velocity and temperature were measured at the six disk sites using an anemometer tree system (TSI Tree System, see Figure 2). The tree system supports six pairs of omnidirectional thermal anemometers (TSI model 1620) and thermistor temperature probes (Yellow Springs Instrument model 705). Each anemometer and thermistor pair was placed approximately 2 cm above and 2 cm away from the naphthalene disk, in such a way as not to disturb the impinging airflow to the disk. The omnidirectional anemometers have a range of 0 - 3 m/s, and a response time of two seconds.

Naphthalene disks were casted using scintillation grade naphthalene. With a melting point of approximately 80°C, the naphthalene was melted and then poured into aluminum disk casting cassettes. The naphthalene quickly hardened at room temperature, after which a nonadhering cover plate was removed to reveal a smooth naphthalene surface. Immediately after casting, the disks were stored individually in airtight containers. All naphthalene disks were allowed to equilibrate in the chamber at 30°C for 24 hours before using. The casting cassettes were appropriately curved to conform to surface curvatures of the upper arm, lower arm, thigh, and calf of the manikin. Cassettes used for the chest and back were flat. For the study, the disks were first mounted into vinyl retainers, which were in turn fastened to the manikin using Velcro straps. The disks were weighed immediately before and after an experiment on a balance sensitive to ±0.01 mg. The duration of each experiment was 55 minutes. The naphthalene weight loss, from 55 minutes of sublimation, were translated to h_c data employing the Chilton-Colburn j-factor analogy between heat and mass transfer [1].

Thoery: heat-mass transfer analogy and the effect of barometric pressure

Heat-mass transfer analogy of a sublimation substance has been traditionally used to accurately predict the forced convective heat transfer coefficient [5,10]. Naphthalene very conveniently sublimates at room temperature and thus has been used by a number of investigators to experimentally determine h_c [2,6,11].

Mass transfer of naphthalene sublimation h_m can be expressed as [6]

$$h_m = R \cdot T_a \cdot \dot{m} \; / \, (P_s - P_a) \tag{1}$$

Assuming the heat of sublimation is negligible, P_s may be considered as equal to the saturated vapor pressure at T_a [9],

$$\log_{10} P_s = 11.55 - 3765/T_a$$

or,

$$P_s = 10^{(11.55-3765/T_a)} \tag{2}$$

The Chilton-Colburn j-factor analogy [1] can be described:

$$\text{for heat transfer} \quad j_h = \frac{h_c}{\rho \cdot c_p \cdot u} (Pr)^{2/3}, \qquad \text{with} \quad Pr = \frac{c_p \cdot \mu}{\kappa} \tag{3}$$

$$\text{for mass transfer} \quad j_m = \frac{P_{AM,n} \cdot h_m}{u} (Sc)^{2/3}, \qquad \text{with} \quad Sc = \frac{\mu}{\rho \cdot D_v} \tag{4}$$

Equating heat and mass transfer j-factor,

$$\frac{h_c}{\rho \cdot c_p \cdot u} (Pr)^{2/3} = \frac{P_{AM,n} \cdot h_m}{u} (Sc)^{2/3} \tag{5}$$

$$h_c = \rho \cdot c_p \left(\frac{Sc}{Pr}\right)^{2/3} \cdot P_{AM,n} \cdot h_m \tag{6}$$

$$h_c = (\rho \cdot c_p)^{1/3} \cdot (\frac{\kappa}{D_v})^{2/3} \cdot P_{AM,n} \cdot h_m \qquad (7)$$

In Equation 7, only ρ and D_v are functions of barometric pressure.

from [3] $$\rho = 1.2929 \cdot \frac{273.15}{T_a} \cdot \frac{P_b}{760.0} \quad \mathrm{kg/m^3} \qquad (8)$$

from [6] $$D_v = \frac{0.0185}{3600} \cdot (\frac{T_a}{273.15})^2 \cdot \frac{760.0}{P_b} \quad \mathrm{m^2/s} \qquad (9)$$

Combining Equations 7 through 9, and substituting in some typical physical properties at 30°C:

$\kappa = 0.02636 \quad \mathrm{W \cdot m^{-1} \cdot K^{-1}}$ $\qquad D_v = 6.330 \cdot 10^{-6} \quad \mathrm{m^2/s}$

$c_p = 1006 \quad \mathrm{J \cdot kg^{-1} \cdot K^{-1}}$ $\qquad \rho = 1.165 \quad \mathrm{kg/m^3}$

$\mu = 1.869 \cdot 10^{-5} \quad \mathrm{kg \cdot m^{-1} \cdot s^{-1}}$

$$Pr = \frac{c_p \cdot \mu}{\kappa} = 0.7133 \qquad Sc = \frac{\mu}{\rho \cdot D_v} = 2.534$$

$P_{AM,n} = 0.319$

Thus,

$$h_c = 1035.7 \cdot (\frac{273.15}{T_a})^{5/3} \cdot (\frac{P_b}{760.0}) \cdot h_m \qquad (10)$$

The relationship between h_c and P_b, previously has been considered as a nonlinear power function. Gagge and Nishi [4] proposed by rational analogy that barometric pressure should change h_c by a factor of $(P_b/760)^{0.55}$, with P_b expressed in units of mmHg. The above theoretical derivation of Equation 10 very clearly shows that h_c varies linearly with $(P_b/760)$, rather than as a power function. This study also seeks to corroborate this linear relationship finding with experimental data.

RESULTS

Table 1 gives the regional air velocity (± dispersion range) at the six naphthalene disk locations: upper arm, lower arm, thigh, calf, chest, and back, on the stationary manikin at sea level setting. Figure 3 shows the local air velocity at the six naphthalene disk sites, at the five P_b: 760.0, 632.4, 522.8, 429.1, and 349.1 mmHg.

Figure 4 gives the local h_c at the six naphthalene disk sites, at the five altitudes. The h_c was computed using Equation 10. For each experimental run, h_c was averaged over the 55 minute experiment period. The results in Figure 4 are the average of 19 runs. A more detailed set of the data presented in Figure 4 is tabulated in Table 2, where h_c is shown with its corresponding standard deviation value. Figure 5 shows the same information as Figure 4 in line plots, to accentuate the linear characteristics.

Analysis of variance (ANOVA) was performed on the h_c values at each disk site, to see if the observed difference was indeed statistically significant. The f-values from the ANOVA tests are listed in Table 3. A f-value > 2.47 indicates

that the h_c sequence does show a significant difference, with $p<0.05$. The Tukey test was then used to determine exactly where the differences lie, and the results are given in Table 4.

The Tukey test was evaluated between h_c at each adjacent elevations. The 0-1, 1-3, 3-4, and 4-6 columns give the test comparison between elevations of 0 and 1520m, 1520m and 3050m, 3050m and 4570m, and 4570m and 6100m, respectively. From the results of the Tukey test in Table 4, for each disk site the difference-between-means are greater than the respective critical-difference-value, indicating that the h_c decrements between adjacent elevation levels are all highly significant ($p<0.05$).

DISCUSSION

The sea level regional air velocities at the six disk sites, as shown in Table 1, represent the base line air velocity level which must be maintained throughout all five hypobaric environments. Unless constant air velocity is maintained, comparisons of h_c from the five environments become meaningless. In our study, a circular fan was used to aid in achieving this base line air velocity level since the present altitude chamber does not stringently monitor the chamber airflow. The ranges of the regional air velocities are displayed in Figure 4 with air velocity (in m/s) on the ordinate, and P_b (in mmHg) as the abscissa. Data for all six disk locations are presented together because all six sets of data display one single result: constant air velocities were maintained throught the five environments. In Figure 4, at each of the six disk sites, bars of equal height signify that constant regional wind speed was indeed maintained for all five elevations. Again, constant

regional air velocities ensure meaningful comparison of convective heat transfer coefficient h_c data.

The six h_c bar graphs in Figure 5 were plotted with h_c (in $W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$) on the ordinate, and again P_b (in mmHg) as the abscissa. Again, all six graphs are presented together to highlight one single thesis: h_c decreased steadily as the barometric pressure decreased from 760 mmHg to 349.5 mmHg. The decreasing trend of h_c was in fact a linear one. This is accentuated in Figure 6 where instead of bar graphs, h_c were plotted as line graphs. In all cases, the decreasing trend of h_c followed a straight line. To further ascertain that the observed linear relationship indeed exists between P_b and h_c, a regression analysis was performed using the complete h_c data set of Table 2. Table 5 gives the results of the regression analysis. For all six disk sites, a linear equation best describes the data with correlation >0.99. The conclusion must be that h_c and P_b exhibit a linear relationship.

The nonlinear power function dependency concept appears to be a residual influence dating from human calorimetric studies of h_c and air velocity, where h_c has been shown to vary as a power function of air velocity [6,7,8]. Most likely, realizing that h_c should vary with P_b, and as a reasonable approximation the power function idea was adopted. The data in Figures 4 and 5, the theoretical derivation of h_c in Equation 10, and the linear regression analysis results in Table 5, very clearly demostrated this power function concept to be groundless and indeed the valid approach is that h_c and P_b exhibit a linear dependency.

The implication of the above results is that at a given hypobaric environment, the convective heat transfer mechanism becomes even more restricted, particularly for human dry heat exchange, than was previously thought. As an example, consider h_c at an elevation of 4570 m (P_b = 429.1 mmHg), and for simplicity assume all other factors, e.g. temperature, humidity, remain constant. From

a power function relationship : $$\left(\frac{P_b}{760.0}\right)^{0.55} = \left(\frac{429.1}{760.0}\right)^{0.55} = 73.0\% \text{ of sea level } h_c\,;$$

a linear relationship: $$\left(\frac{P_b}{760.0}\right) = \left(\frac{429.1}{760.0}\right) = 56.5\% \text{ of sea level } h_c\,.$$

The power function overestimation of h_c in this example is 16.5%, i.e. the convective heat loss is 16.5% less than previously believed. This overestimation of h_c becomes more pronounced as the altitude increases.

When the results of this study are applied to human clothing thermal resistance properties, it appears that at higher elevations, the intrinsic insulation property of a multilayered cold weather clothing system could well be underestimated because convective heat loss is lower then previously proposed. Hence, for example, by dressing according to the original conventional nonlinear power function prediction, an exercising person may well be overdressed and suffer from too much heat storage rather than from the inherent cold of high altitude.

Equation 10 applies implicitly also to hyperbaric conditions although no specific hyperbaric data are presented in this report. At hyperbaric P_b, it can be reasoned that h_c would be generally underestimated using the invalid power function assumption. Such underestimation could have rather significant consequences, since in a hyperbaric environment, convection becomes the one dominant heat transfer mechanism [12].

APPENDIX

Symbols and Terminology

c_p = specific heat ($J \bullet kg^{-1} \bullet K^{-1}$)

D_v = mass diffusivity (m^2/s)

h_c = convective heat transfer coefficient ($W \bullet m^{-2} \bullet K^{-1}$)

h_m = naphthalene mass transfer coefficient (m/s)

j_h = Chilton-Colburn analogy j-factor for heat transfer

j_m = Chilton-Colburn analogy j-factor for mass transfer

$\dot{m}$ = naphthalene sublimation weight loss rate ($kg \bullet m^{-2} \bullet s^{-1}$)

P_a = naphthalene vapor pressure in air (assumed = 0)

P_b = barometric pressure (Torr or mmHg, 1 mmHg = 133.3 Pascal)

$P_{AM,n}$= logarithmic mean density factor for naphthalene sublimating in air (ND)

Pr = Prandtl's number (nondimensional)

P_s = naphthalene surface vapor pressure (Torr or mmHg, 1 mmHg = 133.3 Pascal)

R = naphthalene gas constant ($0.487\ mmHg \bullet m^3 \bullet kg^{-1} \bullet K^{-1}$)

Sc = Schmidt's number (nondimensional)

T_a = ambient temperature (°K)

u = air velocity (m)

κ = thermal conductivity ($W \bullet m^{-1} \bullet K^{-1}$)

μ = viscosity ($kg \bullet m^{-1} \bullet s^{-1}$)

ρ = density (kg/m^3)

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Table 1 Regional air velocity on the stationary manikin, at sea level

naphthalene disk site	regional air velocity (m/s)
Upper Arm	0.538 ± 0.025
Lower Arm	0.576 ± 0.007
Thigh	0.690 ± 0.019
Calf	0.649 ± 0.043
Chest	0.395 ± 0.033
Back	0.231 ± 0.013

air velocity data represent as Means ± SD

Table 2 Regional h_c at 760.0, 632.4, 522.8, 429.1, and 349.5 mmHg

	760.0 mmHg (0 m)	632.4 mmHg (1520 m)	522.8 mmHg (3050 m)	429.1 mmHg (4570 m)	349.5 mmHg (6100 m)
Upper Arm	6.79±0.319	5.27±0.260	4.08±0.199	3.19±0.127	2.46±0.137
Lower Arm	7.37±0.262	5.88±0.279	4.61±0.198	3.66±0.139	2.87±0.154
Thigh	7.45±0.324	6.05±0.321	4.85±0.161	3.94±0.169	3.06±0.140
Calf	7.38±0.394	6.06±0.428	4.96±0.186	4.27±0.290	3.26±0.117
Chest	5.76±0.260	4.37±0.254	3.36±0.183	2.61±0.107	1.99±0.130
Back	3.64±0.283	2.69±0.243	2.08±0.142	1.69±0.127	1.29±0.092

h_c data represent as Means ± SD; unit of h_c is W/(m²•°C)

Table 3 f-value from Analysis of Variance (ANOVA test)

	Upper Arm	Lower Arm	Thigh	Calf	Chest	Back
f	1088.62	1190.62	956.93	485.65	1029.73	414.36

A $f > 2.47$ indicates that significant difference exists ($p<0.05$)

Table 4 Tukey test results

	Difference Between Means				Critical Difference Value
	0 - 1	1 - 3	3 - 4	4 - 6	
Upper Arm	1.520	1.195	0.886	0.730	0.195
Lower Arm	1.497	1.263	0.953	0.795	0.194
Thigh	1.403	1.202	0.912	0.874	0.209
Calf	1.318	1.101	0.688	1.011	0.271
Chest	1.386	1.008	0.758	0.615	0.174
Back	0.947	0.610	0.398	0.392	0.169

column 0-1 compares data between 0 and 1520m elevations
column 1-3 compares data between 1520m and 3050m elevations
column 3-4 compares data between 3050m and 4570m elevations
column 4-6 compares data between 4570m and 6100m elevations

Difference is statistically significant ($p<0.05$) when the Difference-Between-Means is greater than the Critical-Difference-Value

Table 5 Linear regression equation between h_c and P_b

disk site	linear equation from regression analysis	correlation ($p<0.0005$)
Upper Arm	$y = 0.01054\ x - 1.32$	$r = 0.998$
Lower Arm	$y = 0.01100\ x - 1.05$	$r = 0.999$
Thigh	$y = 0.01065\ x - 0.67$	$r = 0.999$
Calf	$y = 0.00979\ x - 0.09$	$r = 0.998$
Chest	$y = 0.00914\ x - 1.30$	$r = 0.997$
Back	$y = 0.00562\ x - 0.75$	$r = 0.994$

In the resulting linear equation $y = mx + b$:

- $y = h_c$ data in $W/(m^2 \cdot °C)$ (as dependent variable)
- $x = P_b$ in mmHg (as independent variable)
- m = slope of straight line
- b = constant (intercept value on the ordinate axis)

Figure legends

Figure 1 Schematic of manikin showing locations of the naphthalene disks

Figure 2 Anemometer tree

Figure 3 Regional air velocities

Figute 4 Local h_c data

Figure 5 Local h_c data as line plots

Figure 1

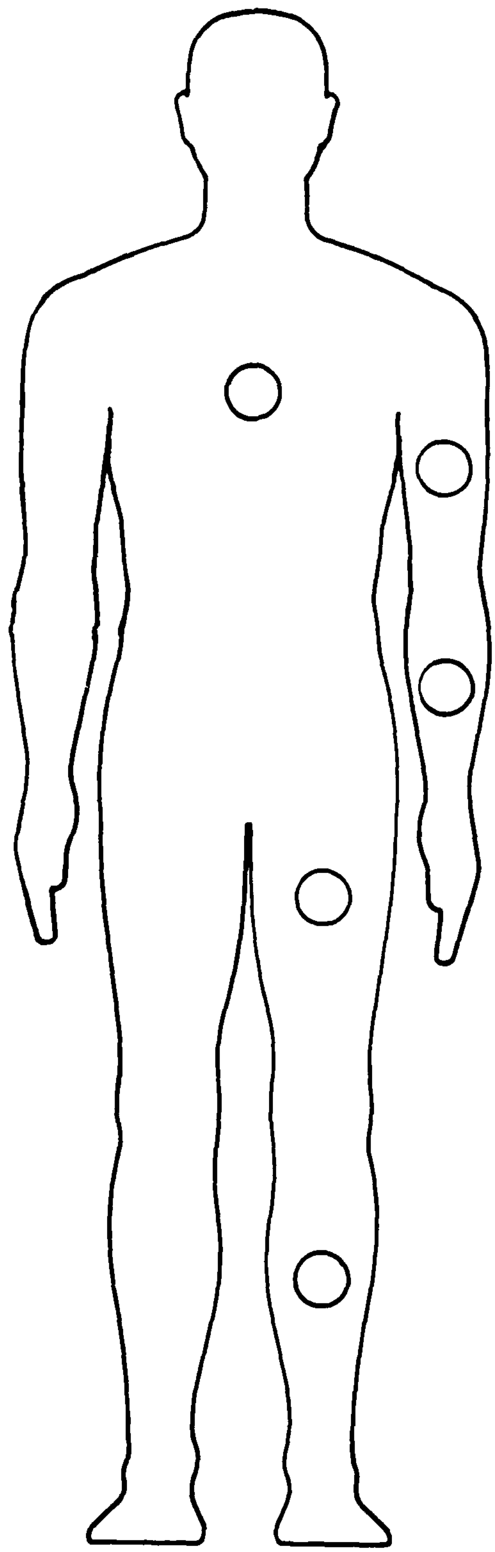

Figure 2

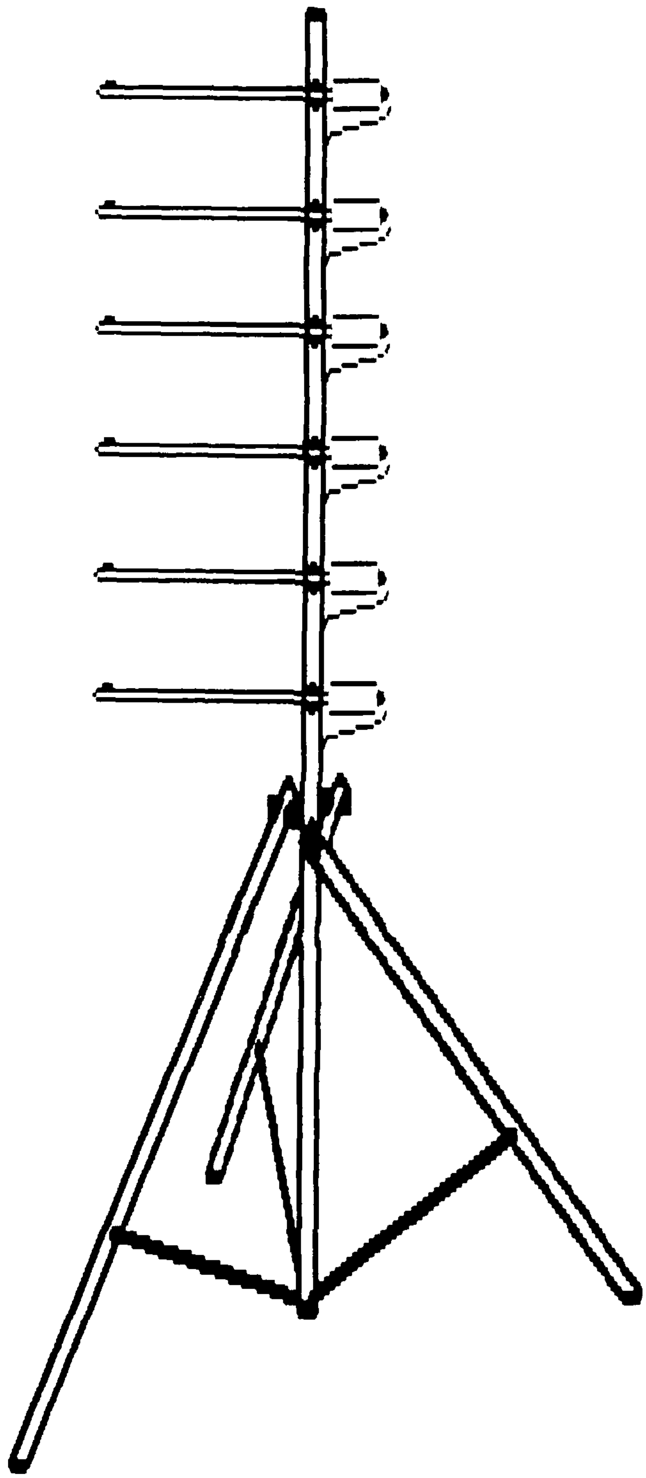

Figure 3 Air Velocity

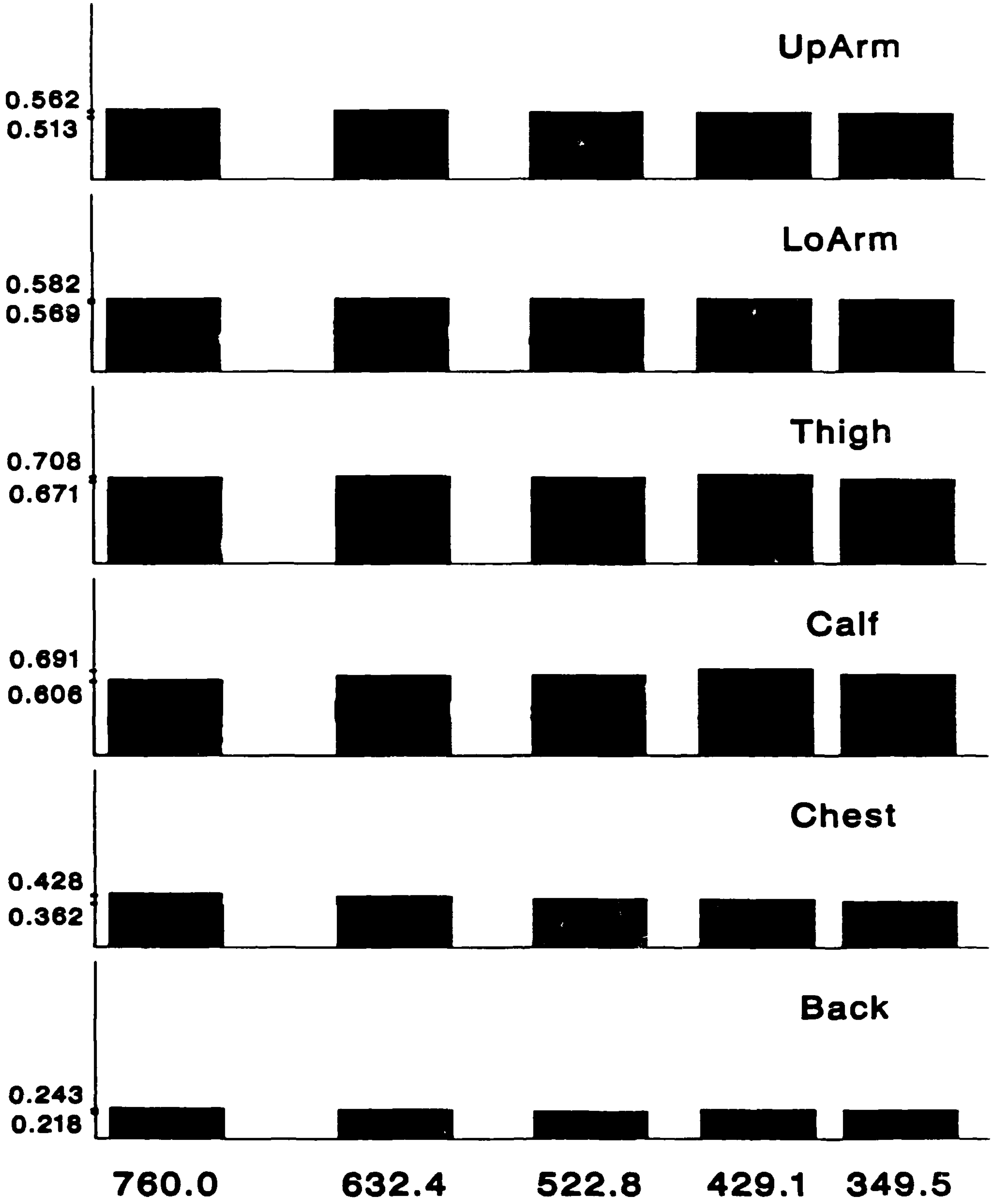

Figure 4 Hypobaric h_c

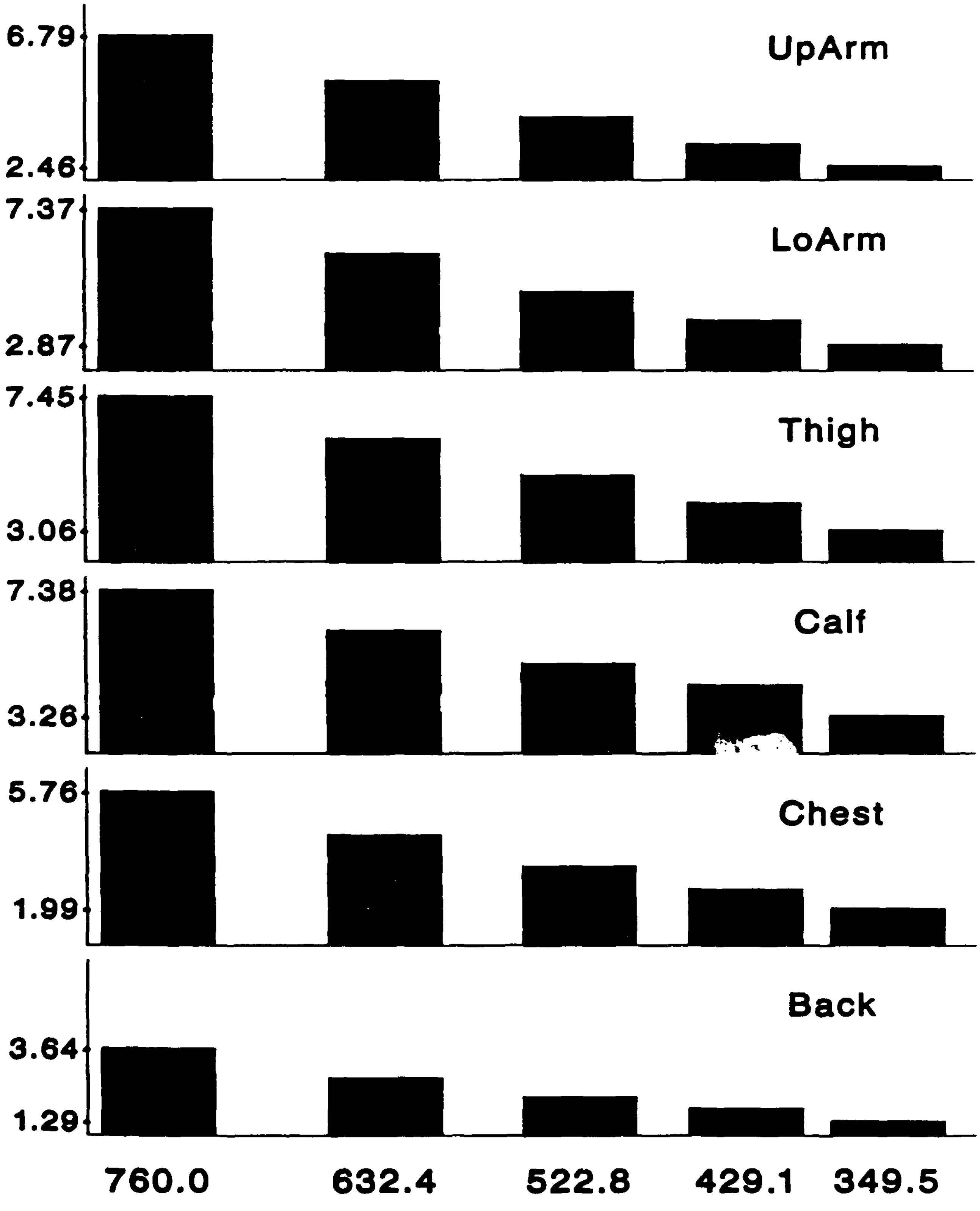

Figure 5 Hypobaric h_c